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COLLEGE OF ENGINEERING

DEPARTMENT OF CHEMICAL AND METALLURGICAL ENGINEERING

SCREENING PROGRAM ON SUPERALLOYS FOR TRISONIC TRANSPORT

Report No. 4

Influence of Notch Acuity on the Notch Strength of René 41, Waspaloy, and D979

UNPUBLISHED PRELIMINARY DATA

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Report No. 4

INFLUENCE OF NOTCH ACUITY ON THE NOTCH STRENGTH OF RENE' 41, WASPALOY, AND D979

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ORA Project 04368

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SUMMARY

Rene' 41, Waspaloy, and D979 materials were subjected to a testing program designed to evaluate the influence of notch acuity on notch strength. Longitudinal and transverse specimens of the alloys were tested at room temperature, 650°, 800°, and 1000°F in the following conditions:

(1) Rene' 41 - Cold reduced 35 percent and aged two hours at 1500°F

(2) Waspaloy - Cold reduced 40 percent and aged two hours at 1500°F

(3) D979 - Cold reduced 50 percent and aged 16 hours at 1100°F.

The theoretical elastic stress concentration factors, K_t's, used in the program were 1.0 (smooth specimens), 1.5, 2.1, 3.1, 8.6 or 9.4, and >20 (ASTM sharp edge-notch).

Notch-tensile strength ratios increased slightly with increasing stress concentration factor to about $K_t = 2.1$ for all the alloys when tested in the transverse direction. Longitudinal specimens from Rene' 41 and Waspaloy at all test temperatures and D979 at room temperature also exhibited a slight increase in notch-tensile strength ratio at low values of K_t. D979, however, tested in the longitudinal direction at elevated temperatures showed a rapidly decreasing notch-tensile strength ratio with increasing value of the stress concentration factor above 1.0.

Rene' 41 displayed at all test temperatures a steady drop in notch strength and, consequently, in notch-tensile strength ratio with increasing notch acuity beyond the slight peak in the ratio which occurred at low values of K_t. Waspaloy exhibited a similar behavior

at room temperature but at elevated temperatures showed an increasing tendency toward exhibiting a minimum in the curve of notch-tensile strength ratio versus K_t. This minimum occurred in the vicinity of $K_t = 9.4$. D979 also showed the presence of a minimum at all temperatures except 650°F. At this temperature, the notch-tensile strength ratio for the alloy dropped rapidly to low values as a function of notch acuity and then remained relatively constant with increasing K_t.

Duplicate tests on D979 material at 650°F showed increased scatter of results at the lower K_t values for longitudinal specimens. Transverse specimens exhibited a relatively constant amount of data scatter as a function of K_t.

INTRODUCTION

As part of a screening program designed to evaluate the usefulness of selected sheet materials in the construction of a supersonic transport plane, a study is being carried out at the University of Michigan to determine the utility of the heat-resistant superalloys.

Six different superalloys in a total of seventeen conditions of prior history are in the process of being evaluated. Materials suitable for use in a supersonic transport must possess adequate strength properties and be sufficiently stable under conditions of aerodynamic heating to maintain these properties. It is especially important for the materials to possess and maintain adequate fracture toughness (resistance to unstable crack propagation).

D979 alloy in the cold reduced 50 percent and aged 16 hours at 1100°F condition displayed generally good properties during initial testing. However, longitudinal specimens tested at 650°, 800°, and 1000°F repeatedly fractured at stresses below the 0.2 percent offset yield strength. These fractures occurred in a brittle manner at pin holes, fillets, and in the gage section of the specimens under the extensometer collars. In an attempt to understand this behavior in a promising material, an investigation was initiated to determine what influence notches of low and intermediate acuities had on the strength properties of D979 alloy.

Two other alloys in addition to the D979 were included in this investigation, Rene' 41 and Waspaloy. These alloys were chosen because they also had shown excellent properties in tests carried out as part of the screening program.

EXPERIMENTAL MATERIALS

The alloys used in this investigation were in the form of 0.025-inch sheet material. Their reported chemical compositions in weight percent are listed in Table I.

The conditions in which each of the three alloys were tested were as follows:

(1) Rene' 41 - Cold reduced 35 percent and aged two hours at 1500°F

(2) Waspaloy - Cold reduced 40 percent and aged two hours at 1500°F

(3) D979 - Cold reduced 50 percent and aged 16 hours at 1100°F.

Specimen blanks were cut from the cold worked sheet material and then aged in an electric furnace prior to being machined into finished specimens.

EXPERIMENTAL PROCEDURES

The influence of notch acuity on the notch strength of the three alloys was evaluated at room temperature, 650°, 800°, and 1000°F. The theoretical elastic stress concentration factors used in the program were 1.5, 2.1, 3.1, and either 8.6 or 9.4. In addition, smooth specimens (K_t = 1.0) and specimens with ASTM sharp edge-notches (K_t >20) were tested.

Properties in both the longitudinal and transverse directions were measured to avoid misleading results from anisotropy effects which might be present.

Test Specimens

Unnotched Specimens

The configuration of the smooth specimens used to measure unnotched properties (K_t = 1.0) is shown in Figure 1a. Specimens were prepared from rectangular blanks by milling. Ten specimens were machined at a time, using a fixture to clamp the blanks together and assure accurate alignment throughout the machining operations.

Notched Specimens

The geometry of the specimens with K_t's of 1.5, 2.1, 3.1, and 8.6 or 9.4 is shown in Figure 1b. Only the notch root radius changed with the stress concentration factor. The values of the notch root radius for the different K_t's are as follows:

Stress Concentration Factor, K_t	Notch Root Radius, inch
1.5	0.250
2.1	0.100
3.1	0.040
8.6	0.0044
9.4	0.0036
>20	<0.0007

In the screening program, the resistance of the materials to catastrophic crack growth was evaluated using sharp edge-notched specimens of a design similar to that recommended by the ASTM (Ref. 1). The configuration of this specimen is shown in Figure 1c.

As was the case with the unnotched specimens, ten blanks were machined at one time, using a second fixture to maintain alignment. The reduced section was first milled to size. The notches were then ground almost to size with an alundum wheel on a 60-degree included angle. Notch roots for K_t's of 1.5 to 9.4 were lapped to final dimensions. Notch roots for the sharp (K_t >20) notches were finished by manually drawing a sharp carbide tool through the notches, using a shaper, until the required dimensions were obtained. Root radii and net section width were then measured using 50X optical comparator.

Tensile Tests

All tensile tests were conducted with a 60,000-pound capacity hydraulic tensile machine. Unnotched samples were strained at an approximate strain rate of 0.01 inch per inch per minute up to about 2 percent deformation. The strain rate was then increased to about 0.05 inch per inch per minute until failure. Notched specimens were loaded at a rate of 1000 psi net section stress per second. The test procedures followed those of References 1 and 2.

The specimens for tests at elevated temperatures were heated with an electric resistance furnace. Temperature variation along the gage length of the specimens was held to within ± 5 °F. Indicated test temperature was within ± 3 °F of the nominal temperature for all tests.

RESULTS AND DISCUSSION

The notch strengths and the notch-tensile strength ratios for the three materials were evaluated as a function of notch acuity (stress concentration factor) at room temperature, 650°, 800°, and 1000°F. The results indicated that under certain conditions minimums in the notch-tensile strength ratio can occur at a lower notch acuity than obtained with the ASTM sharp edge-notch.

Rene' 41

Table II lists the data obtained for Rene' 41 in the study of the influence of notch acuity on notch strength and on notch-tensile strength ratio.

Rene' 41 exhibited a slight increase in notch-tensile strength ratio with initial increase in K_t (to about 3.1), then decreased with further increases in K_t (Fig. 2). The literature indicates that most heat-resistant alloys show this type of behavior (Ref. 3). The ASTM sharp edge-notch (K_t >20) gave the lowest values of notch-tensile strength ratio at all temperatures and for both directions of testing. The longitudinal and transverse specimens behaved very much alike except in two instances. First, replicate room temperature tests on specimens with K_t's of 8.6 showed that specimens taken in the direction parallel to the direction of rolling (longitudinal) had significantly higher values of notch-tensile strength ratio than did specimens taken transverse to the direction of rolling (0.95 and 0.97 as opposed to 0.79 and 0.79). The second exception occurred at 1000°F where the notch-tensile strength ratio fell off much more rapidly for the longitudinal specimens than it did for the transverse specimens. In this case, the transverse specimens maintained a high notch-tensile

strength ratio out to values of K_t >20.

Waspaloy

Waspaloy at room temperature exhibited only a slight peak in notch-tensile strength ratio at low K_t values (Fig. 3). The notch-tensile strength ratio decreased somewhat when the value of K_t exceeded about 3.1. At elevated temperatures, the peak persisted in the curve of notch-tensile strength ratio versus K_t, however, it shifted to a lower value of K_t at 1000°F as is shown in Figure 3. Table III lists the data obtained for Waspaloy during this investigation.

Figure 3 shows the variation in notch-tensile strength ratio with theoretical stress concentration factor for Waspaloy. The principle feature of this figure is the minimum which appears in the elevated temperature curves at a K_t of about 9.4. At 650°F, this minimum only occurs in specimens taken in the longitudinal direction, however, at 800°F and 1000°F the minimum occurs both in the longitudinal and transverse specimens. Restating this in other terms, at 800°F and 1000°F Waspaloy has lower notch strength when the value of K_t is about 9.4 than it does when K_t is in excess of 20 (ASTM sharp edge-notch). Figure 3 also shows that the drop-off in notch-tensile strength ratio occurs at lower values of K_t as the temperature is raised.

While Waspaloy did show evidence of lower notch strength at a stress concentration factor of 9.4 than it did at a value of greater than 20, the notch-tensile strength ratio did not fall below 0.7 and, consequently, the existence of the minimum should not cause undue concern.

D979

Table IV lists the results obtained in the study of the influence of notch acuity on the notch strength and on the notch strength-tensile strength ratio of D979 alloy. Figure 4 shows the curves of notch-

tensile strength ratio versus K_t at the different test temperatures.

This alloy exhibited a marked variation in properties with specimen orientation. At room temperature, values of notch-tensile strength ratio for specimens taken transverse to the direction of rolling were, in every case, significantly higher than those for specimens taken parallel to the direction of rolling. At 650°F, there is a cross-over at a K_t value of about 13, above which the longitudinal specimens show a higher notch-tensile strength ratio. At 800°F, this cross-over took place at a stress concentration factor of approximately 5 and at 1000°F it occurred at a value of about 4.

Minimums appear in the curves of notch-tensile strength ratio versus notch acuity at about K_t = 9.4 for both longitudinal and transverse specimens at all temperatures except 650°F. Longitudinal specimens at 650°F exhibit a rapid drop in the ratio with increasing notch severity up to K_t = 3.1. Beyond this value, the notch-tensile strength ratio remains relatively constant. Transverse D979 specimens at 650°F exhibit a continual decrease in notch-tensile strength ratio with increasing K_t.

The transverse specimens of this material showed a peak in the notch-tensile strength ratio at about K_t = 1.5. This peak decreased in magnitude with increasing temperature and at 1000°F, little evidence of its existence remained. Longitudinal specimens showed no evidence of such a peak except possibly at room temperature.

Duplicate tests were run on this alloy at 650°F. The specimens taken in the transverse direction showed little variability between samples while the longitudinal specimens showed significant variability of results at K_t's of 1.5, 2.1, and 3.1. This is illustrated in Figure 4.

A study of Figure 4 shows that at elevated temperatures the notch-tensile strength ratio of the longitudinal specimens decreased rapidly with increasing K_t. The fillets and pin holes of the smooth

specimens have stress concentration factors of 1.15 and 1.75, respectively. For a value of K_t equal to 1.75, the notch-tensile strength ratio of D979 at 650°F is 0.77, at 800°F, 0.86, and at 1000°F, 0.74. This deterioration of notch-tensile strength ratio at a stress concentration factor of only 1.75 strongly indicates that the notch sensitivity of this alloy was responsible for its many failures at pin holes during tests of longitudinal smooth specimens at 650°, 800°, and 1000°F. This same explanation could also apply to the failures which occurred at the fillets. In this case (K_t = 1.15), while the values of the notch-tensile strength ratio were not as low (0.91 at 650°, 0.97 at 800°, to 0.92 at 1000°F), they quite probably were sufficiently low to have caused the failures which occurred at the fillets. This theory is enforced when one takes into account the significant amount of data scatter which occurred in D979 alloy in the region of the lower values of K_t.

CONCLUSIONS

A limited evaluation of the influence of notch acuity on the notch strength of Rene' 41, Waspaloy, and D979 sheet materials at room temperature, 650°, 800°, and 1000°F has been completed. The data obtained give a good indication of the behavior of the materials under the influence of notches less severe than the sharp notch used in the original screening program of possible supersonic transport materials.

The conclusions reached are summarized as follows:

(1) The notch-tensile strength ratio generally had maximum values at K_t's of 1.5 to 3.1 regardless of specimen orientation or test temperature with the exception of D979 tested parallel to the direction of rolling at 650°, 800°, and 1000°F where the ratios fell off sharply at $K_t > 1.0$.

(2) In at least one case for each alloy, at intermediate K_t's of 8.6 to 9.4 the notch-tensile strength ratio fell to values as low as or lower than those obtained for $K_t > 20$. This raises the question of whether the ASTM sharp edge-notch specimen is the ultimate test for fracture toughness in the screening program.

(3) The cause of brittle fracture of longitudinal unnotched specimens of D979 below the 0.2% offset yield strength at 650°, 800°, and 1000°F in the pin holes and at the fillets is its pronounced sensitivity to dull notches ($K_t > 1$ to 2).

(4) Waspaloy exhibited the least anisotropy and loss of notch strength with increasing notch severity at the temperatures investigated. In no case did notch-tensile strength ratio fall below 0.7.

(5) Rene' 41 exhibited little anisotropy and the loss of notch strength appeared severe only for $K_t > 20$ at 650°, 800°, and 1000°F.

REFERENCES

1. Special ASTM Committee: Fracture Testing of High-Strength Sheet Materials. Chap. I. ASTM Bull. Jan. 1960, pp 29-40; Chap. II, ASTM Bull. Feb. 1960, pp 18-28.

2. Manning, C. R., Jr., and Heimerl, G. J.: An Evaluation of Some Current Practices for Short-Time Elevated-Temperature Tensile Tests of Metals. Langley Research Center, Langley Field, Virginia, NASA TN-D-420, September, 1960.

3. Voorhees, H. R., and Freeman, J. W.: Notch Sensitivity of High-Temperature Alloys. WADC Technical Report 59-470, March 1960.

Table I

CHEMICAL COMPOSITION OF EXPERIMENTAL MATERIALS

Alloy	C	Si	Mn	Cr	Ni	Mo	Ti	Al	W	P	S	B	Fe	Co	Zr
D979	0.078	0.15	0.18	15.02	43.97	4.06	3.04	1.02	3.57	0.007	0.006	0.12	Bal	---	---
Waspaloy	0.08	0.07	0.04	19.63	Bal	4.26	2.99	1.40	---	---	0.007	0.0048	2.30	13.49	0.03
Rene' 41	0.10	0.06	0.06	18.48	Bal	9.37	3.19	1.42	---	---	0.007	0.0047	2.20	10.43	---

D979 alloy (Heat W23211) was produced by the Allegheny Ludlum Steel Corporation

Waspaloy (Heat B119) and Rene' 41 (Heat R216) were produced by the Metallurgical Products Division of the General Electric Company

Table II

NOTCH STRENGTH AND NOTCH-TENSILE STRENGTH RATIO OF RENE' 41
AS A FUNCTION OF NOTCH ACUITY

Stress Concentration Factor K_t	Notch Strength (1000 psi)							
	Room Temp.		650°F		800°F		1000°F	
	L[a]	T[b]	L	T	L	T	L	T
1	244	237	229	222	221	217	221	218
1.5	252 264	248 256	235	234	231	230	226	222
2.1	267 266	258 261	228	234	230	228	210	221
3.1	263 268	254 260	232	226	233	238	202	224
8.6	241 237	186 188	169	171	179	174	161	181
>20	196 195	182	138	155	142	142	116	140

Stress Concentration Factor K_t	Notch-Tensile Strength Ratio							
	Room Temp		650°F		800°F		1000°F	
	L	T	L	T	L	T	L	T
1	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1.5	1.01 1.06	1.05 1.08	1.03	1.05	1.05	1.06	1.02	1.01
2.1	1.07 1.07	1.09 1.10	1.00	1.05	1.04	1.05	0.95	1.02
3.1	1.06 1.08	1.07 1.10	1.01	1.02	1.06	1.10	0.91	1.03
8.6	0.97 0.95	0.79 0.79	0.74	0.77	0.81	0.80	0.73	0.83
>20	0.79 0.78	0.77	0.60	0.70	0.64	0.65	0.52	0.64

[a] - Longitudinal specimen orientation

[b] - Transverse specimen orientation

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Table III

NOTCH STRENGTH AND NOTCH-TENSILE STRENGTH RATIO OF WASPALOY AS A FUNCTION OF NOTCH ACUITY

Stress Concentration Factor K_t	Notch Strength (1000 psi)							
	Room Temp.		650°F		800°F		1000°F	
	L[a]	T[b]	L	T	L	T	L	T
1	237	232	211	204	204	199	204	199
1.5	246	235	220 218	218 212	212	208	206	202
2.1	246	236	221 221	211 221	214	210	207	209
3.1	244	242	224 222	210 220	210	214	174	173
9.4	221	216	155 161	185 182	144	152	160	151
>20	212	201	163	149	172	166	169	166

Stress Concentration Factor K_t	Notch-Tensile Strength Ratio							
	Room Temp.		650°F		800°F		1000°F	
	L	T	L	T	L	T	L	T
1	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1.5	1.04	1.01	1.04 1.03	1.07 1.04	1.04	1.05	1.01	1.02
2.1	1.04	1.02	1.05 1.05	1.03 1.08	1.05	1.06	1.02	1.05
3.1	1.03	1.04	1.06 1.05	1.03 1.08	1.03	1.08	0.85	0.87
9.4	0.94	0.93	0.73 0.76	0.91 0.89	0.71	0.76	0.78	0.76
>20	0.90	0.87	0.77	0.73	0.84	0.83	0.83	0.83

[a] - Longitudinal specimen orientation

[b] - Transverse specimen orientation

Table IV

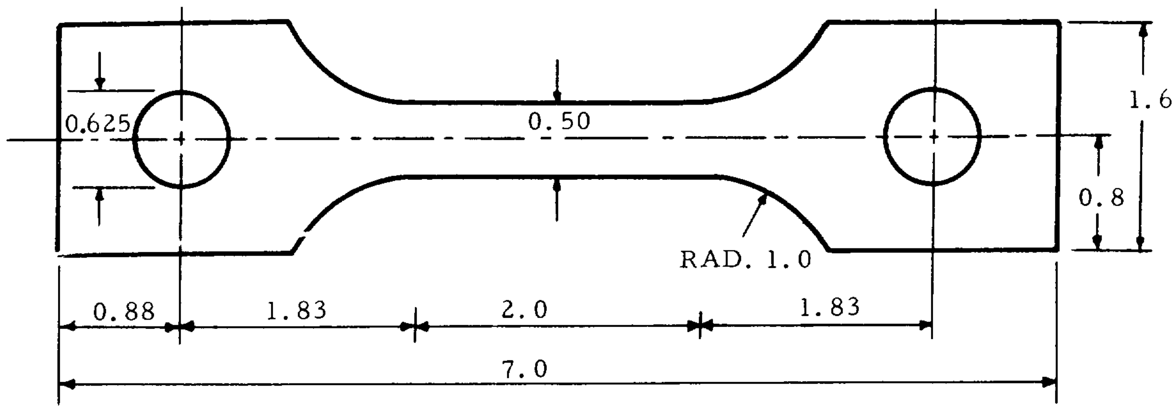
NOTCH STRENGTH AND NOTCH-TENSILE STRENGTH RATIO OF D979
AS A FUNCTION OF NOTCH ACUITY

Stress Concentration Factor K_t	Notch Strength (1000 psi) Room Temp. L[a]	T[b]	650°F L	T	800°F L	T	1000°F L	T
1	273	262	244	237	235	233	214	234
1.5	276	283	218 175	251 240	214	240	170	236
2.1	261	280	206 163	232 220	188	209	146	212
3.1	240	262	151 187	174 184	166	189	135	169
9.4	171	173	144 149	151 139	143	123	122	104
>20	180 176	190	143 132	123 126	158	136	126	115 120

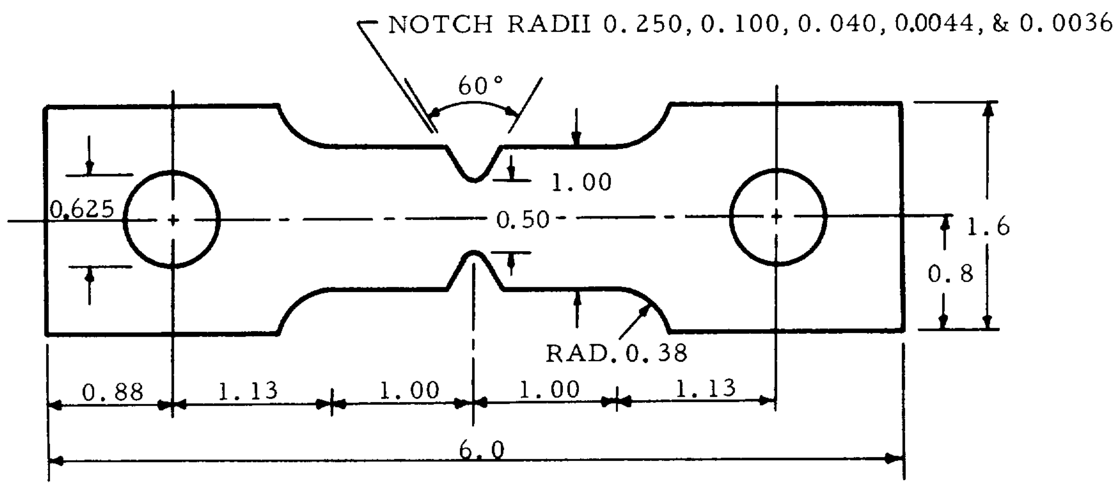
Stress Concentration Factor K_t	Notch-Tensile Strength Ratio Room Temp. L	T	650°F L	T	800°F L	T	1000°F L	T
1	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1.5	1.01	1.09	0.89 0.72	1.06 1.01	0.91	1.03	0.80	1.01
2.1	0.96	1.07	0.84 0.67	0.98 0.93	0.80	0.90	0.68	0.91
3.1	0.88	1.00	0.62 0.77	0.73 0.78	0.71	0.81	0.63	0.72
9.4	0.60	0.66	0.59 0.61	0.64 0.59	0.61	0.53	0.59	0.44
>20	0.65	0.73	0.59 0.54	0.52 0.53	0.67	0.58	0.59	0.49 0.51

[a] - Longitudinal specimen orientation

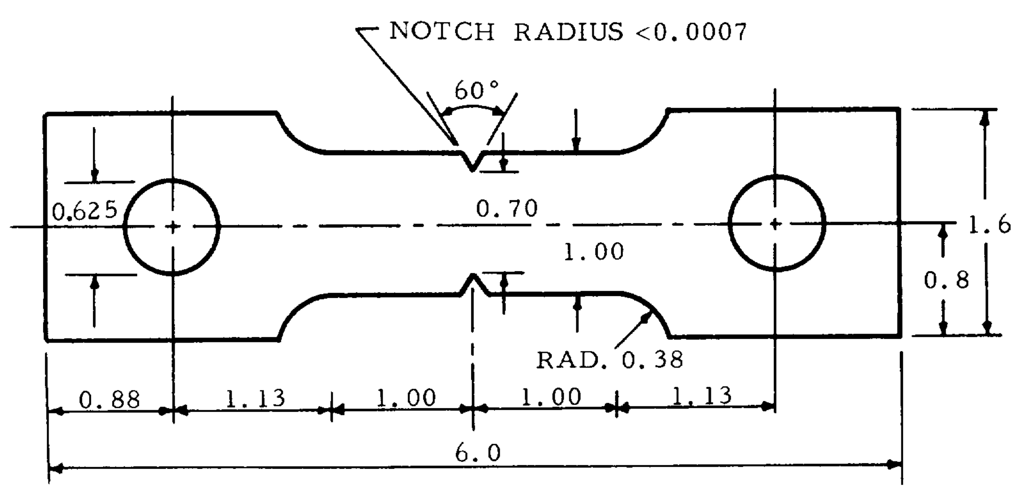
[b] - Transverse specimen orientation



1a. Smooth (unnotched) specimen ($K_t = 1.0$).



1b. Notched specimen for K_t = 1.5, 2.1, 3.1, 8.6, and 9.4.



1c. ASTM sharp edge-notched specimen ($K_t > 20$)

Fig. 1 Tensile Test Specimens (All dimensions in inches)

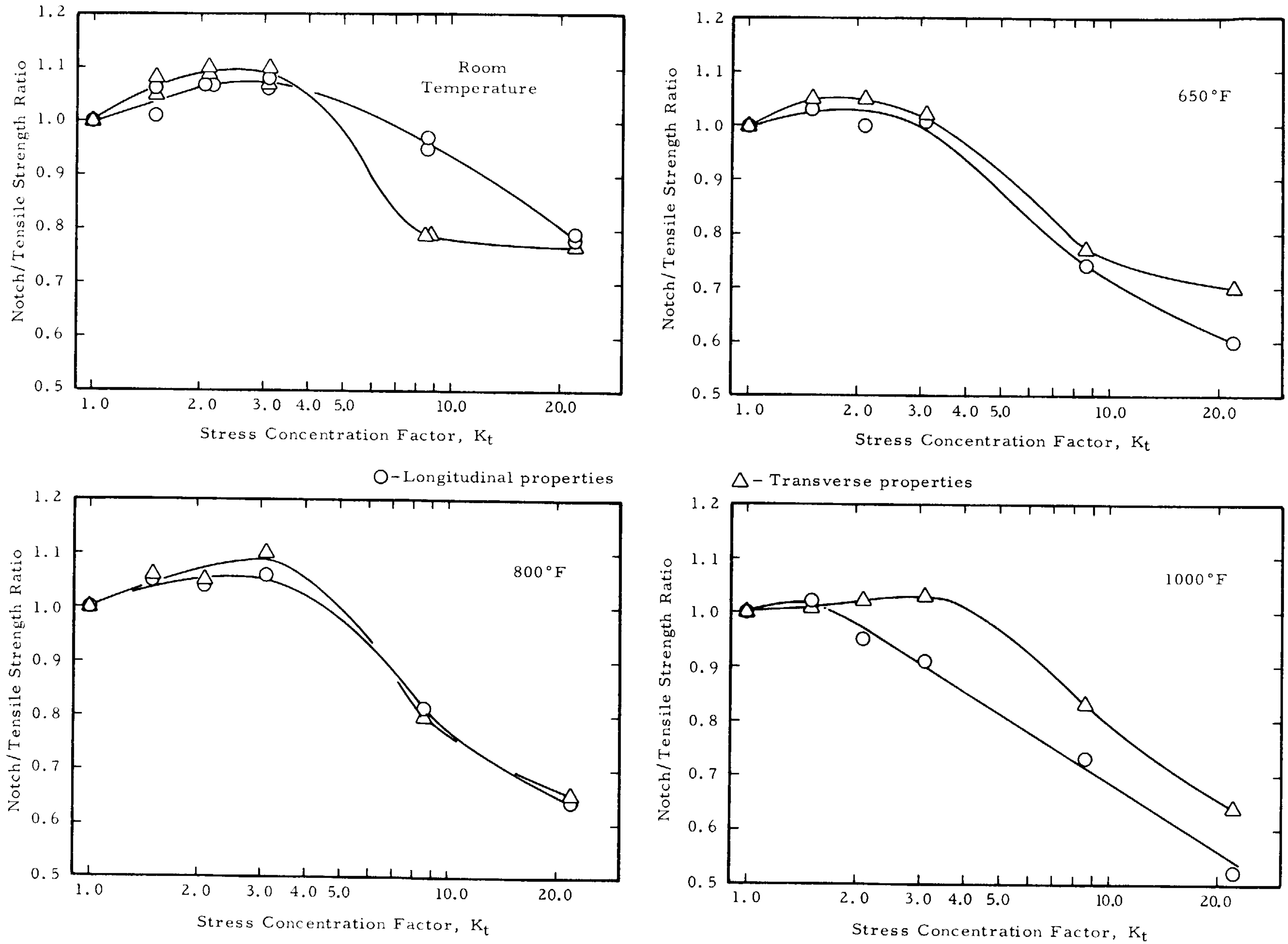


Fig. 2 Influence of Notch Acuity on the Tensile Properties of Rene' 41.

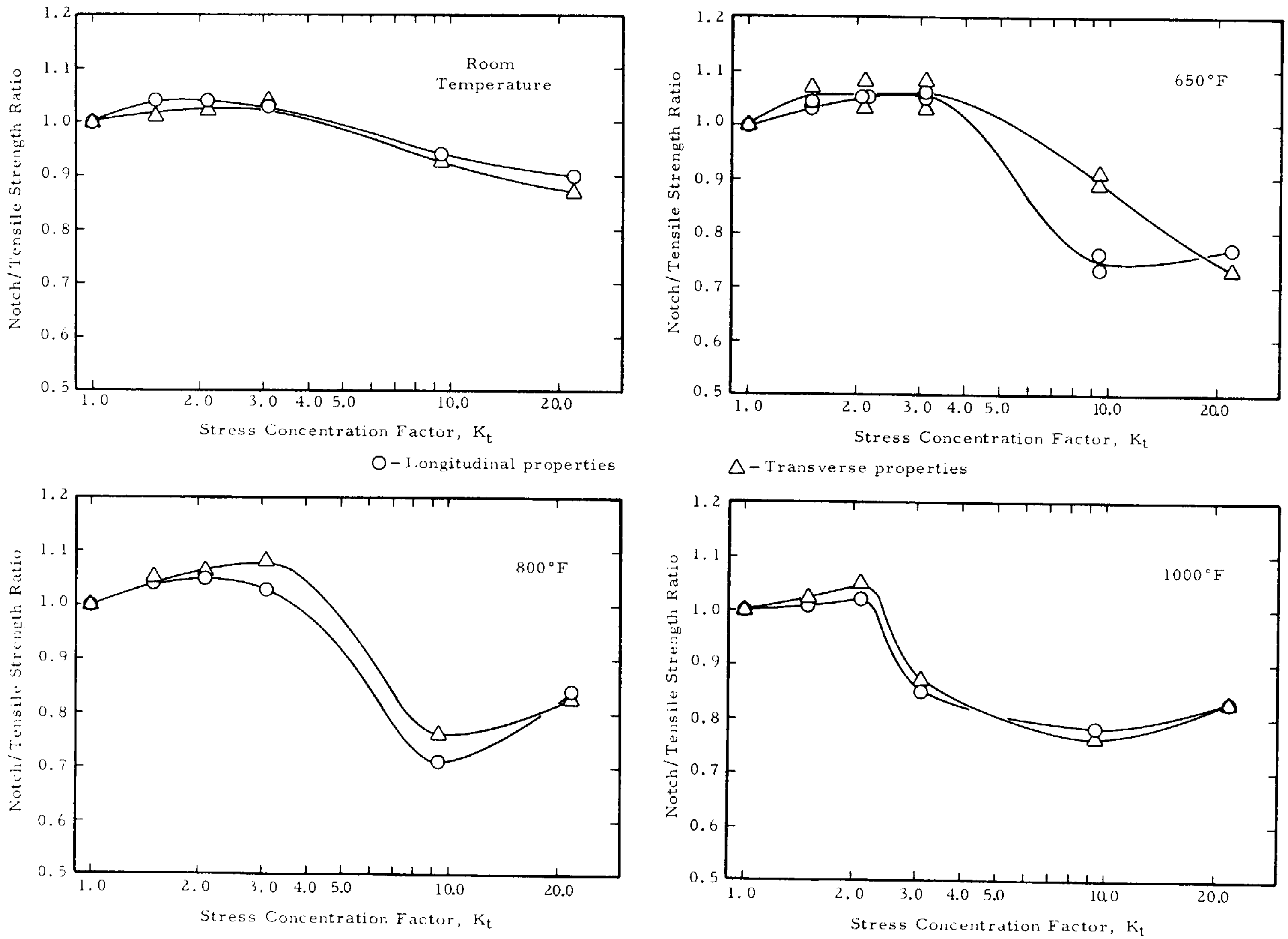


Fig. 3 Influence of Notch Acuity on the Tensile Properties of Waspaloy.

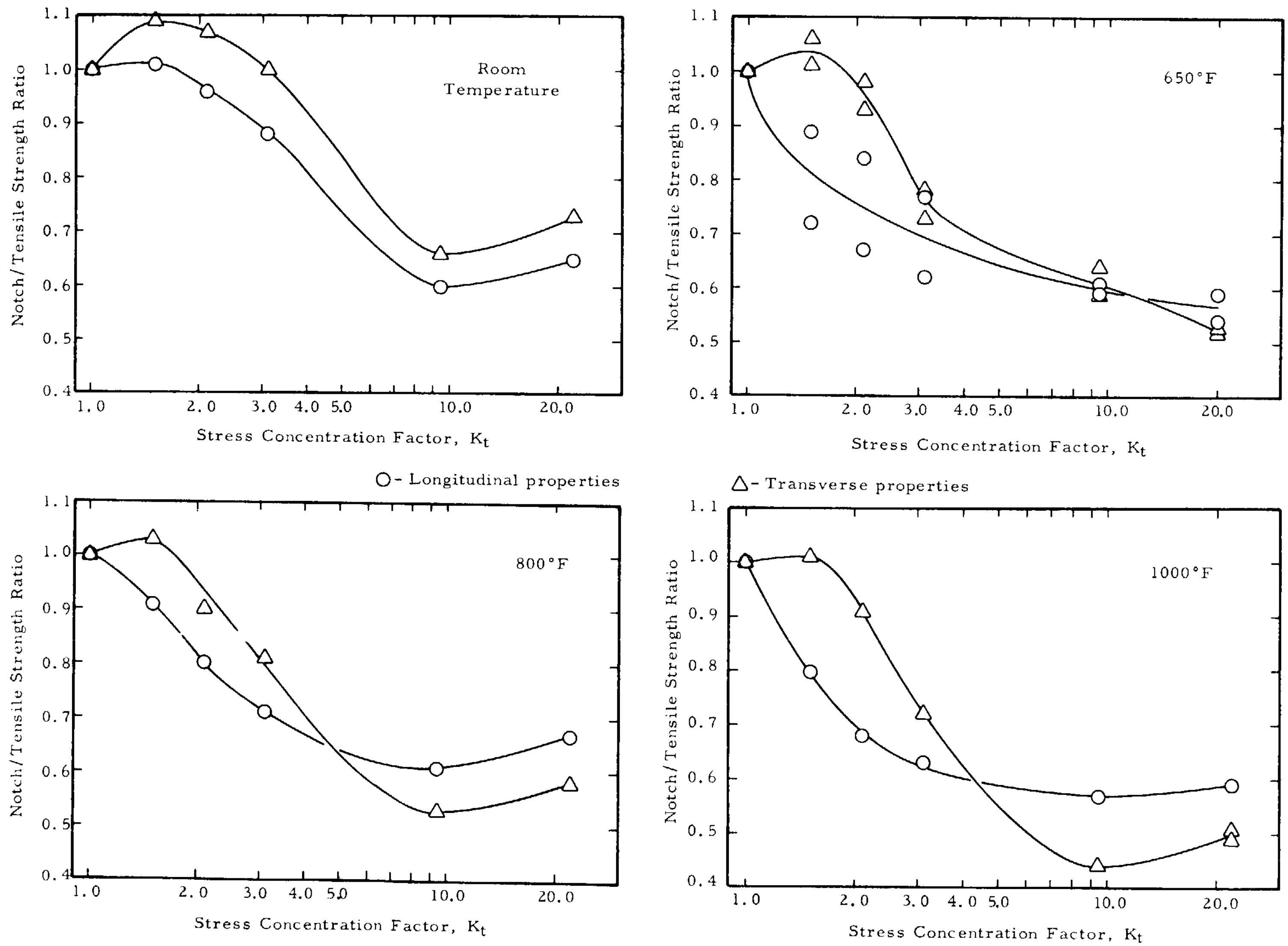


Fig. 4 Influence of Notch Acuity on the Tensile Properties of D979.